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Potasek et al.

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(54) **MEMS GYROS WITH QUADRATURE REDUCING SPRINGS**

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G01C 19/5712 (2012.01)

(52) **U.S. Cl.**
CPC ***G01C 19/56*** (2013.01); ***G01C 19/5712*** (2013.01)

(58) **Field of Classification Search**
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(Continued)

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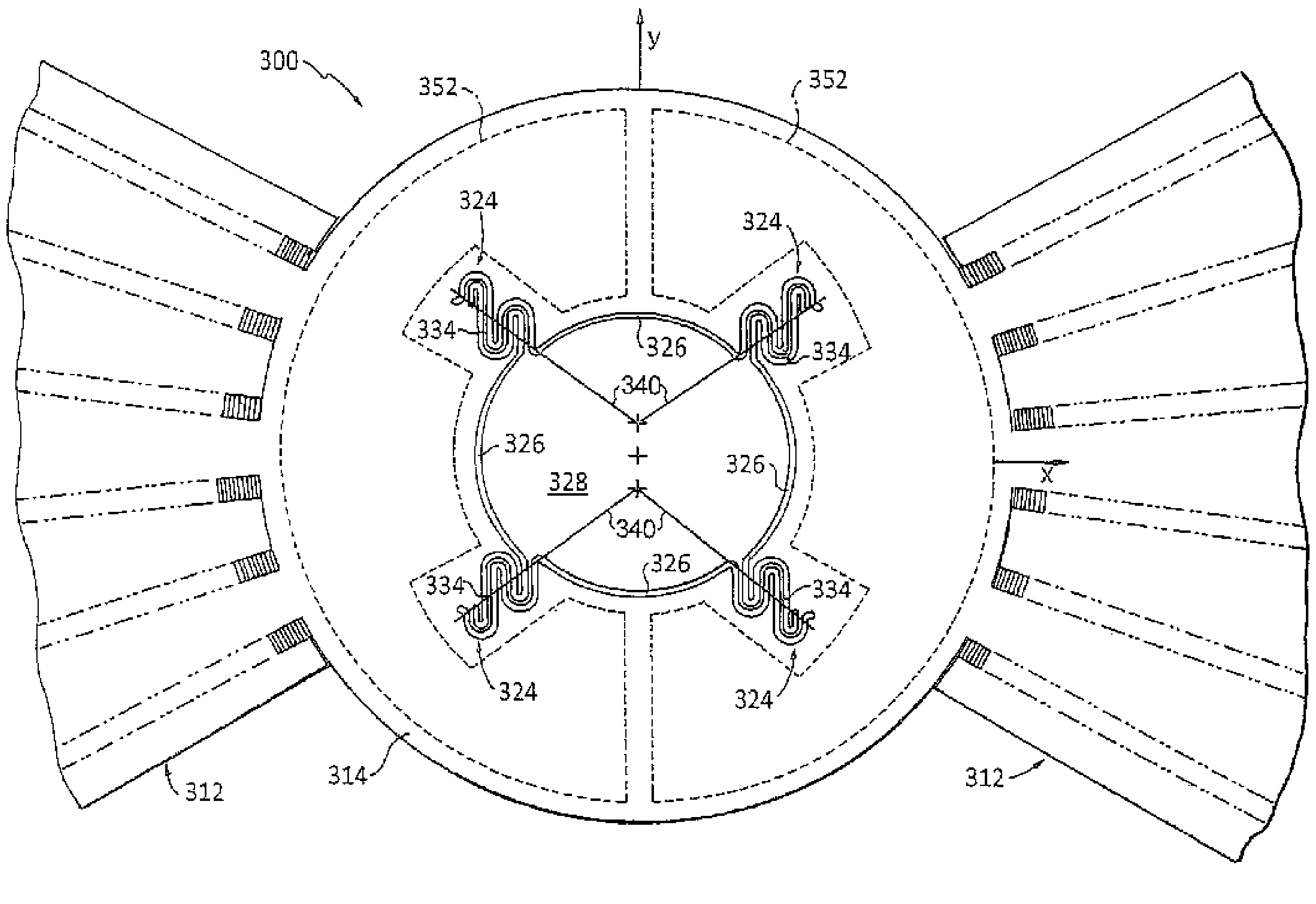
(57) **ABSTRACT**

Spring set configurations that include an advantageous combination of spring geometries are disclosed. Spring elements having curved and straight sections, orientation of spring element anchor points with respect to the common radius, orientation of spring element segments with respect to a specific axis, balance of the length of spring elements about the common radius, and mass balance about the common radius can be used to mitigate unwanted out of plane motion. The spring set provides planar motion while reducing undesired out of plane motion making MEMS devices substantially insensitive to the process-induced etch angle variations of the spring elements. The spring set can be used in a MEMS gyro device which maintains the desired resonant modes and consistently low quadrature error even with process variations in manufacturing causing undesirable etch angles.

7 Claims, 9 Drawing Sheets



(58) **Field of Classification Search**

USPC 73/504.12, 504.13, 504.14, 504.02, 73/504.04, 504.11

See application file for complete search history.

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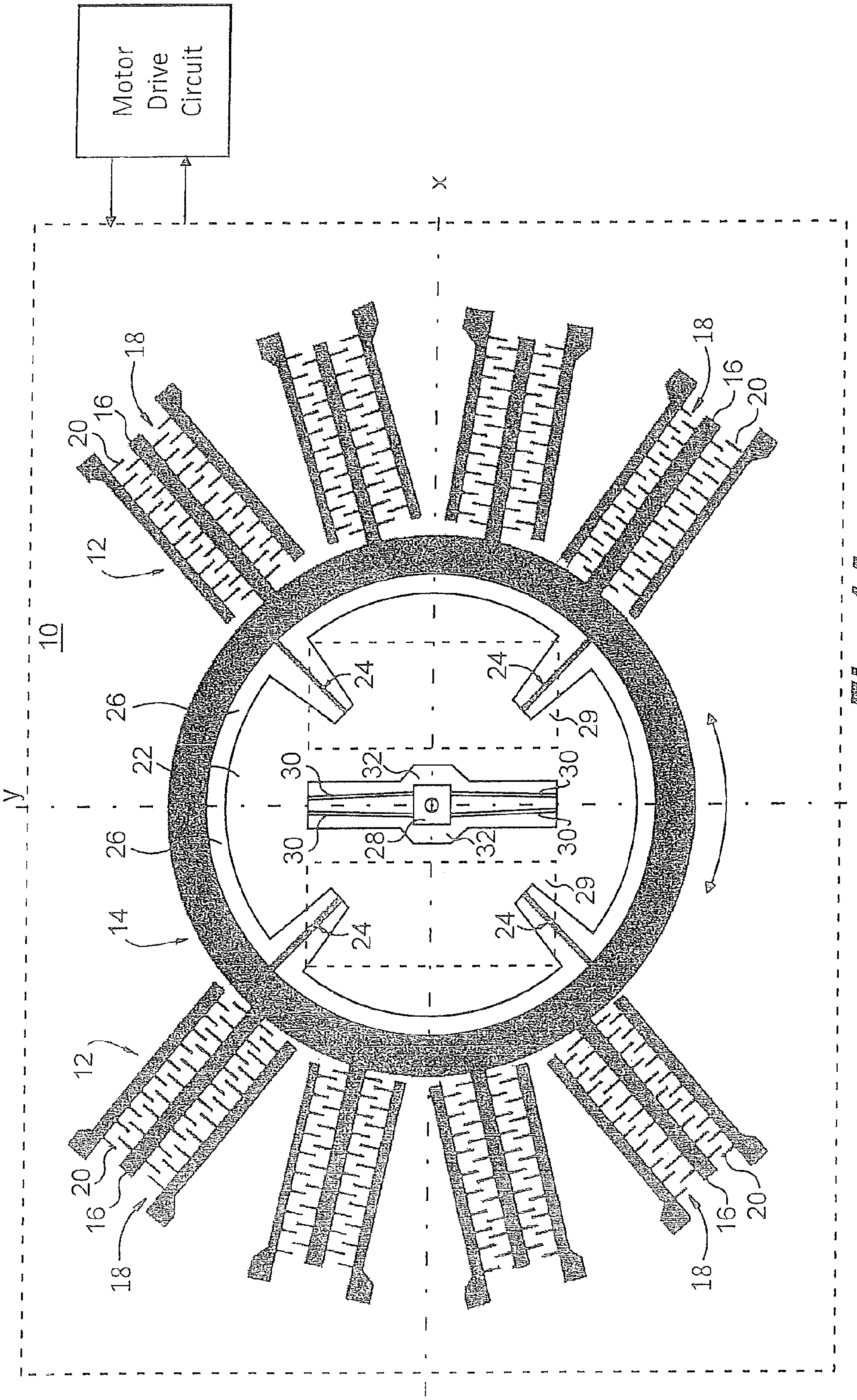


Fig. 1A
(Prior Art)

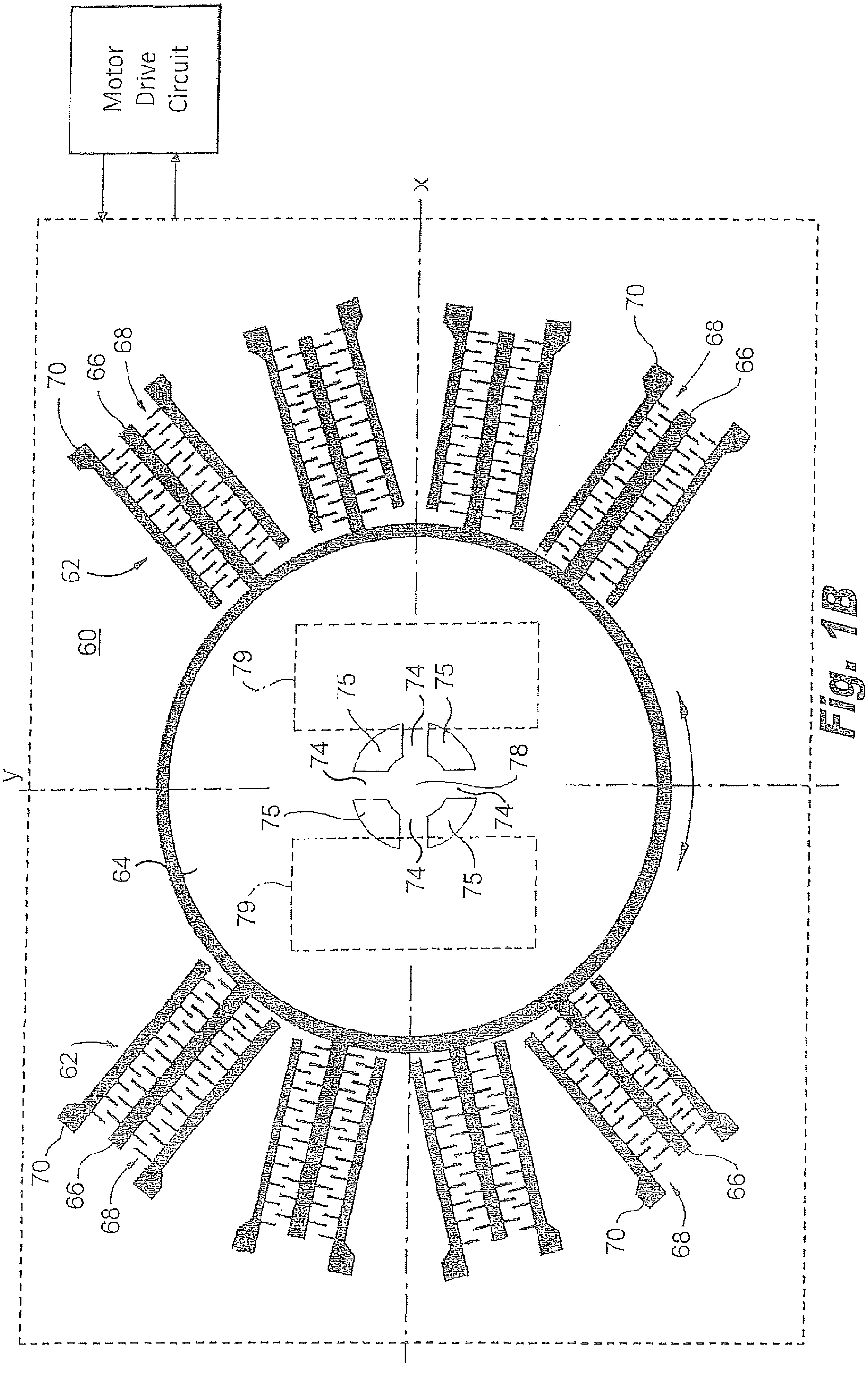
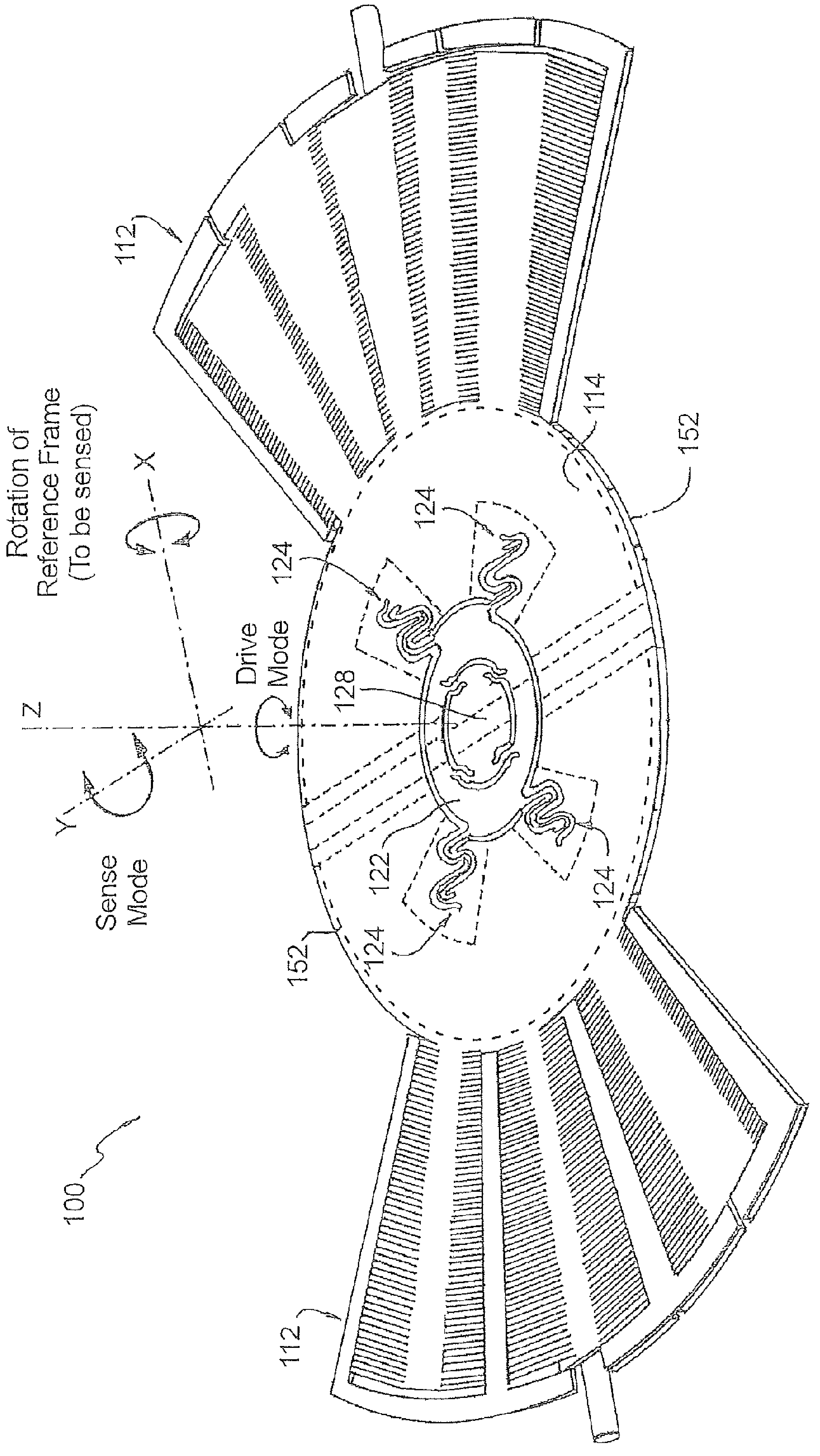


Fig. 1B (Prior Art)


Rotation of
Reference Frame
(To be sensed)
X
Z
Y
Drive
Mode
Sense
Mode
100
112
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114
152
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128
122

Fig. 2

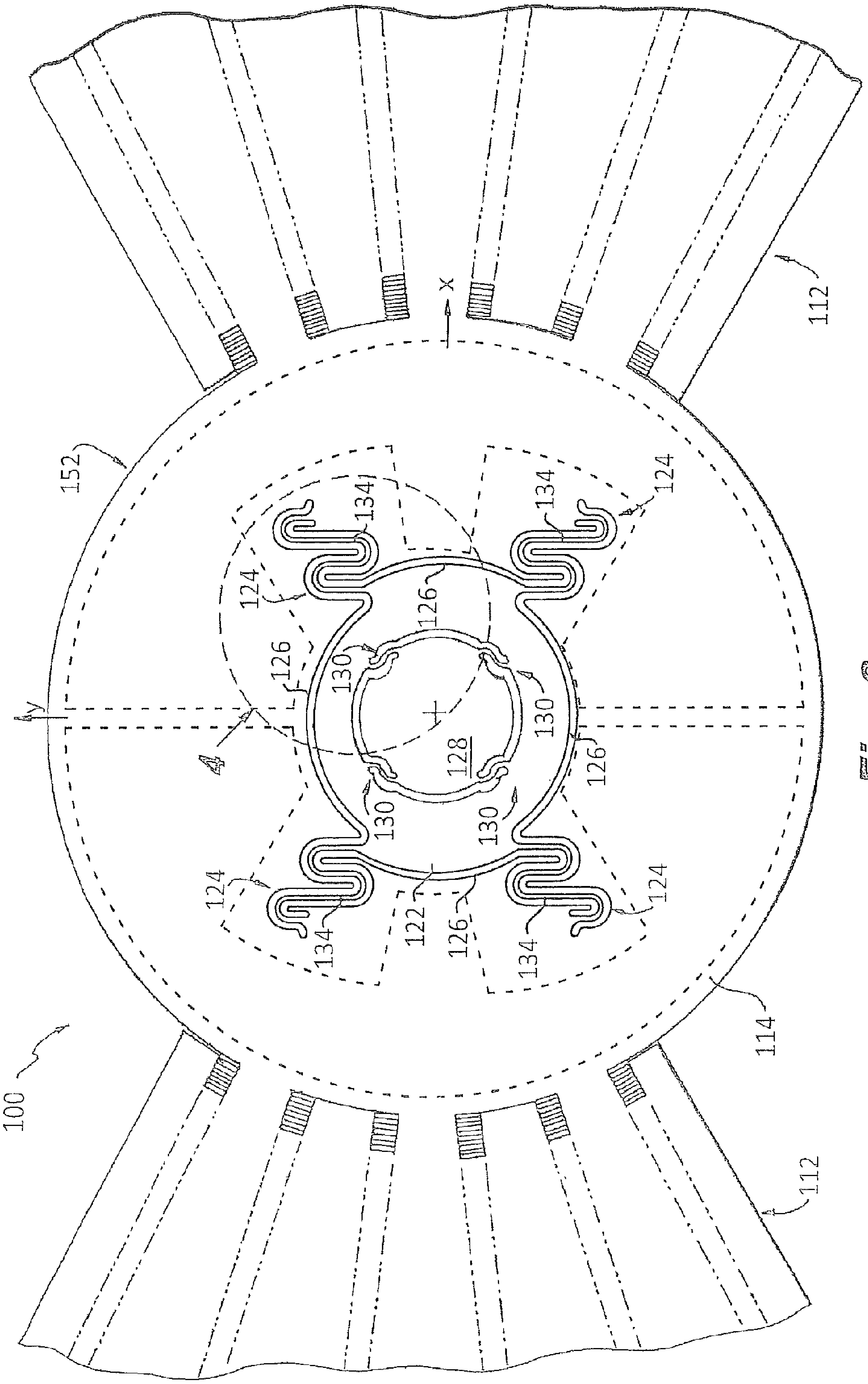
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Fig. 3

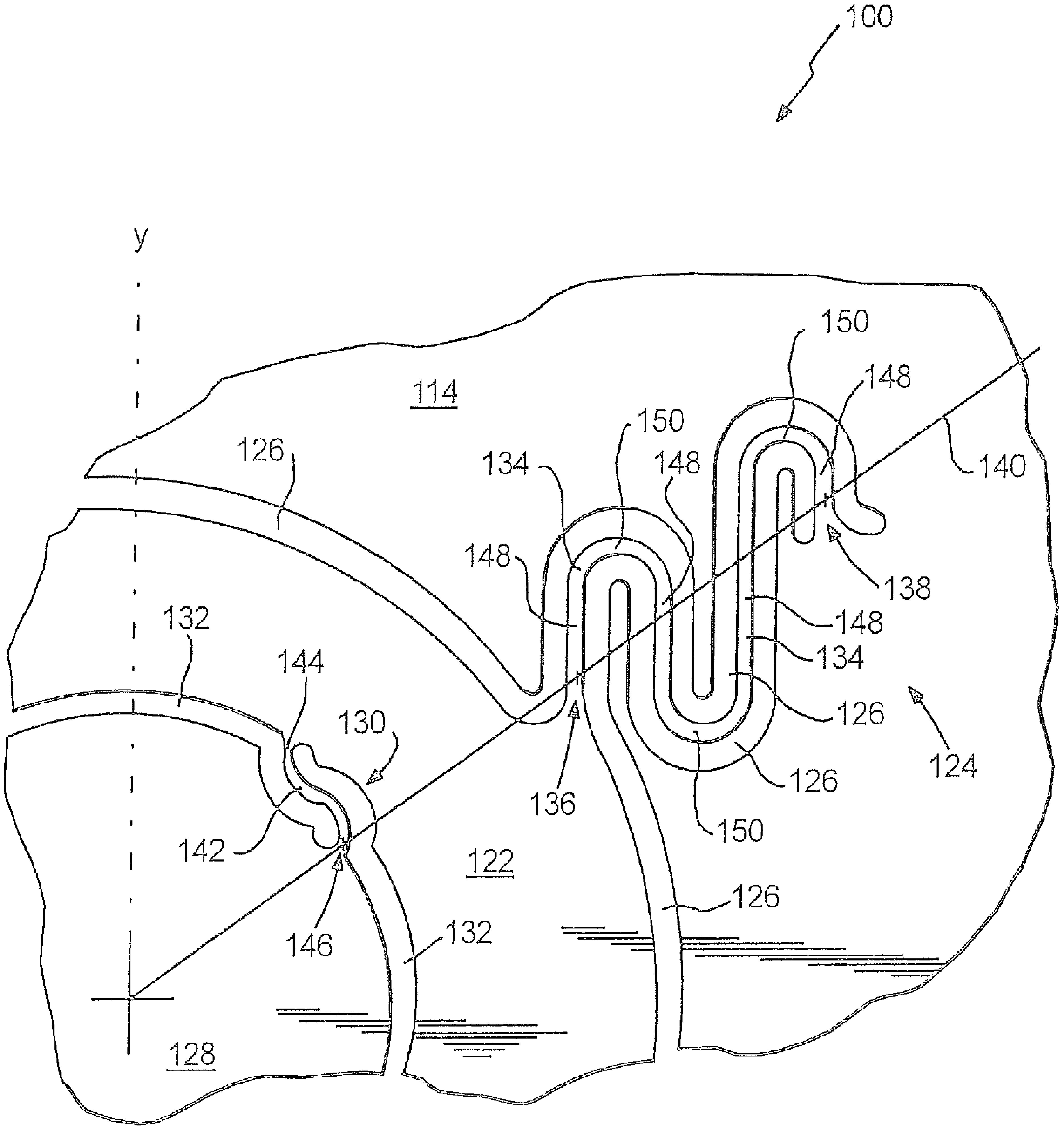
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Fig. 4

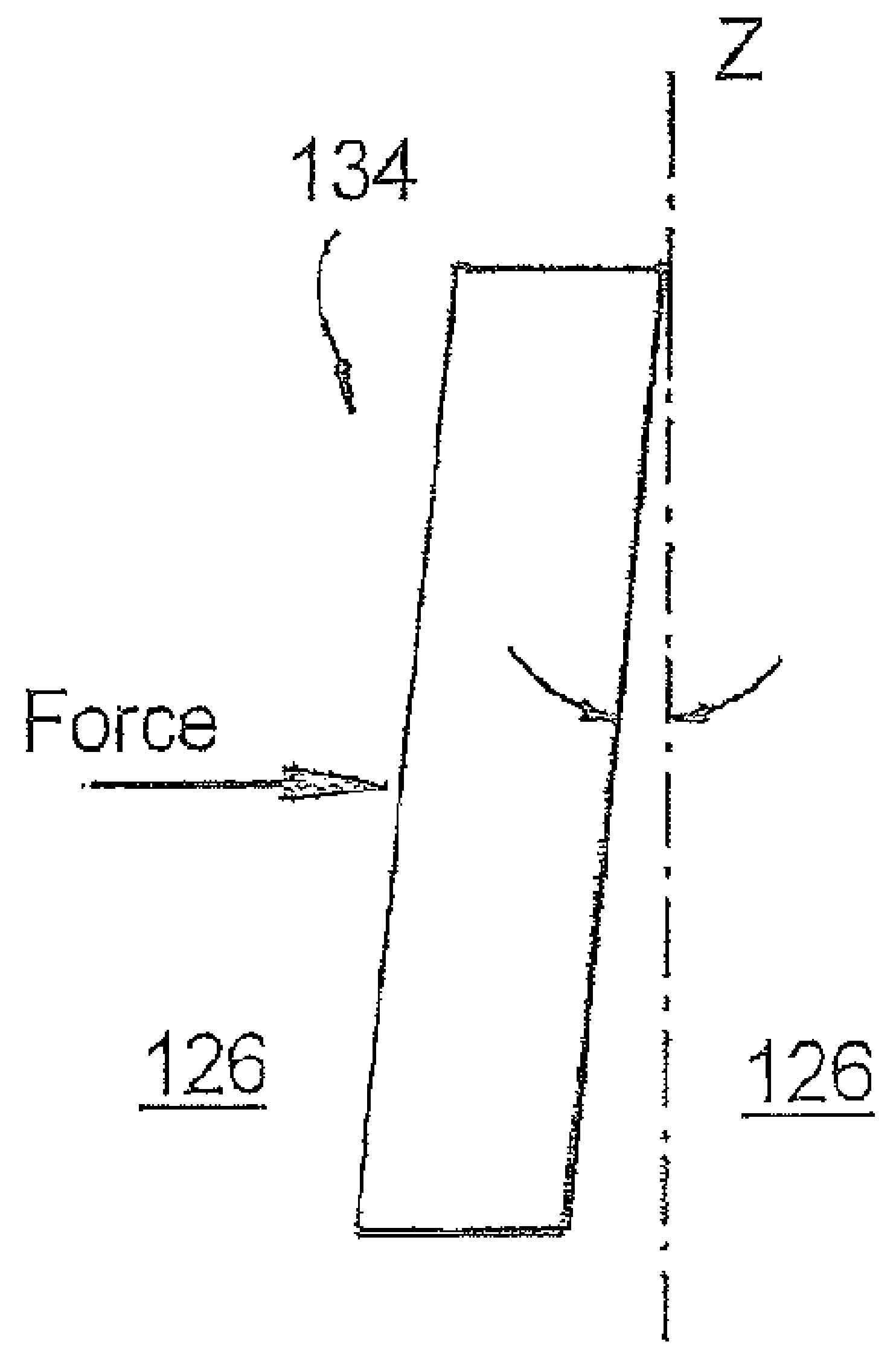


Fig. 5

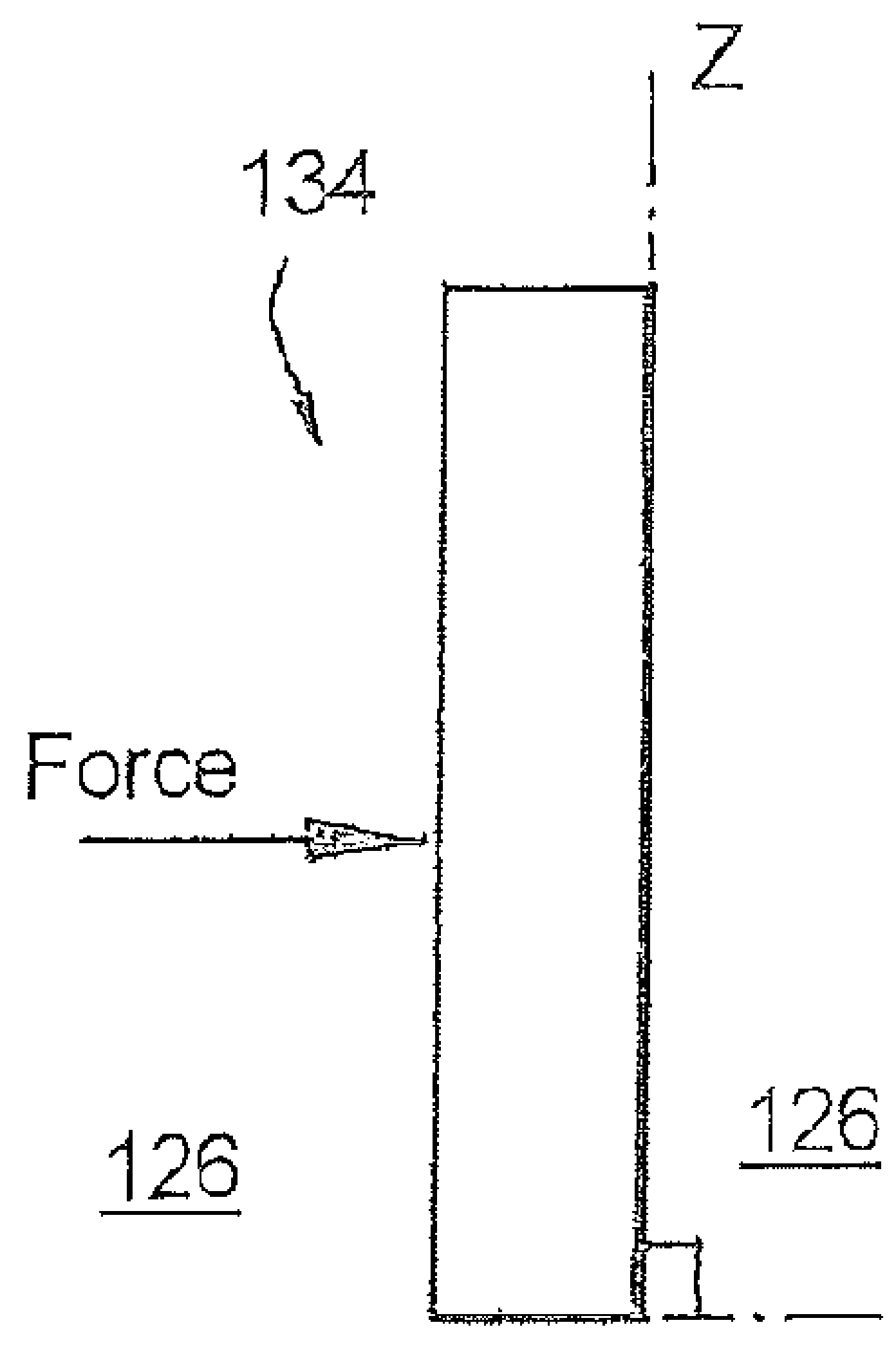


Fig. 6

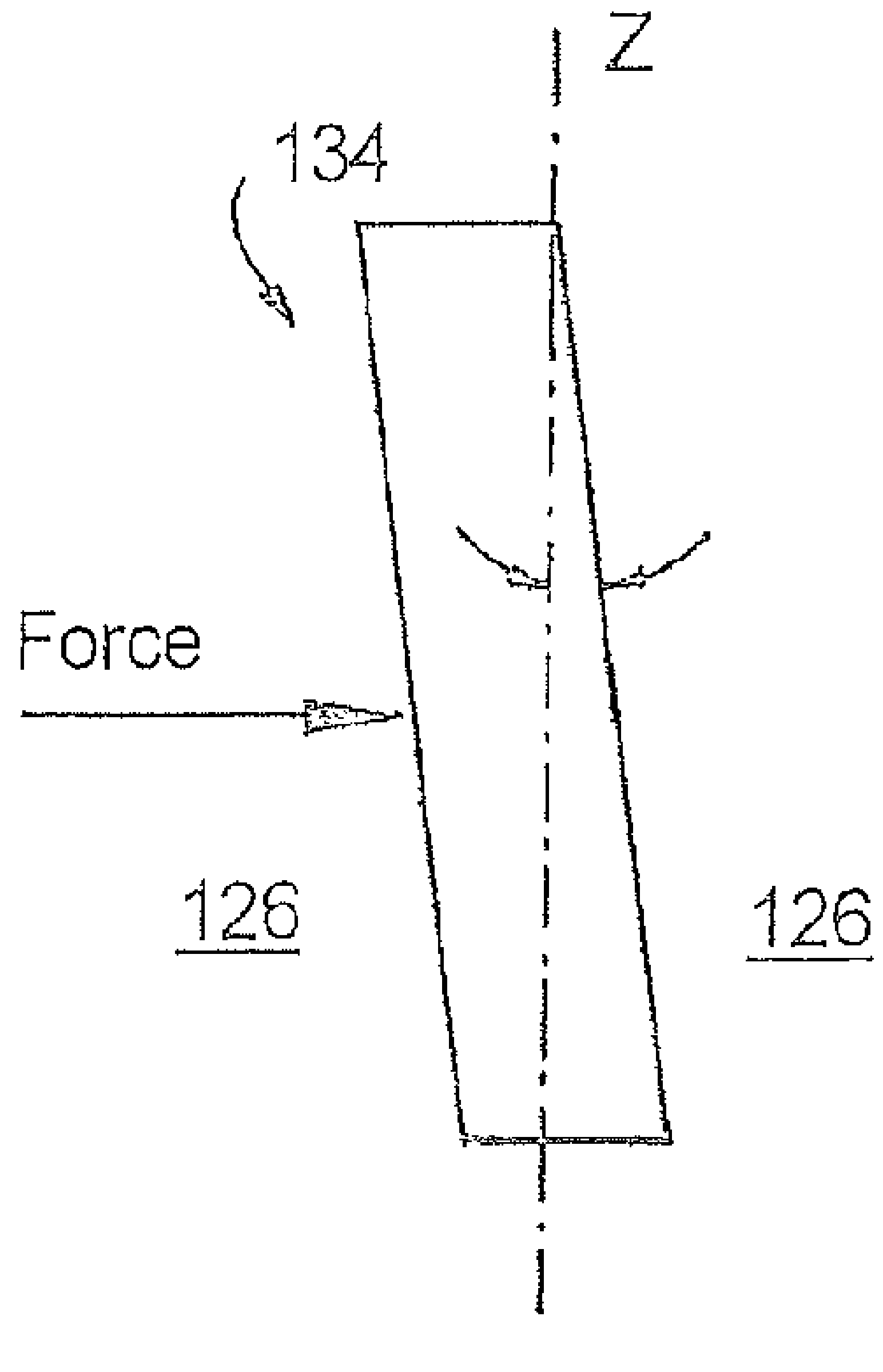


Fig. 7

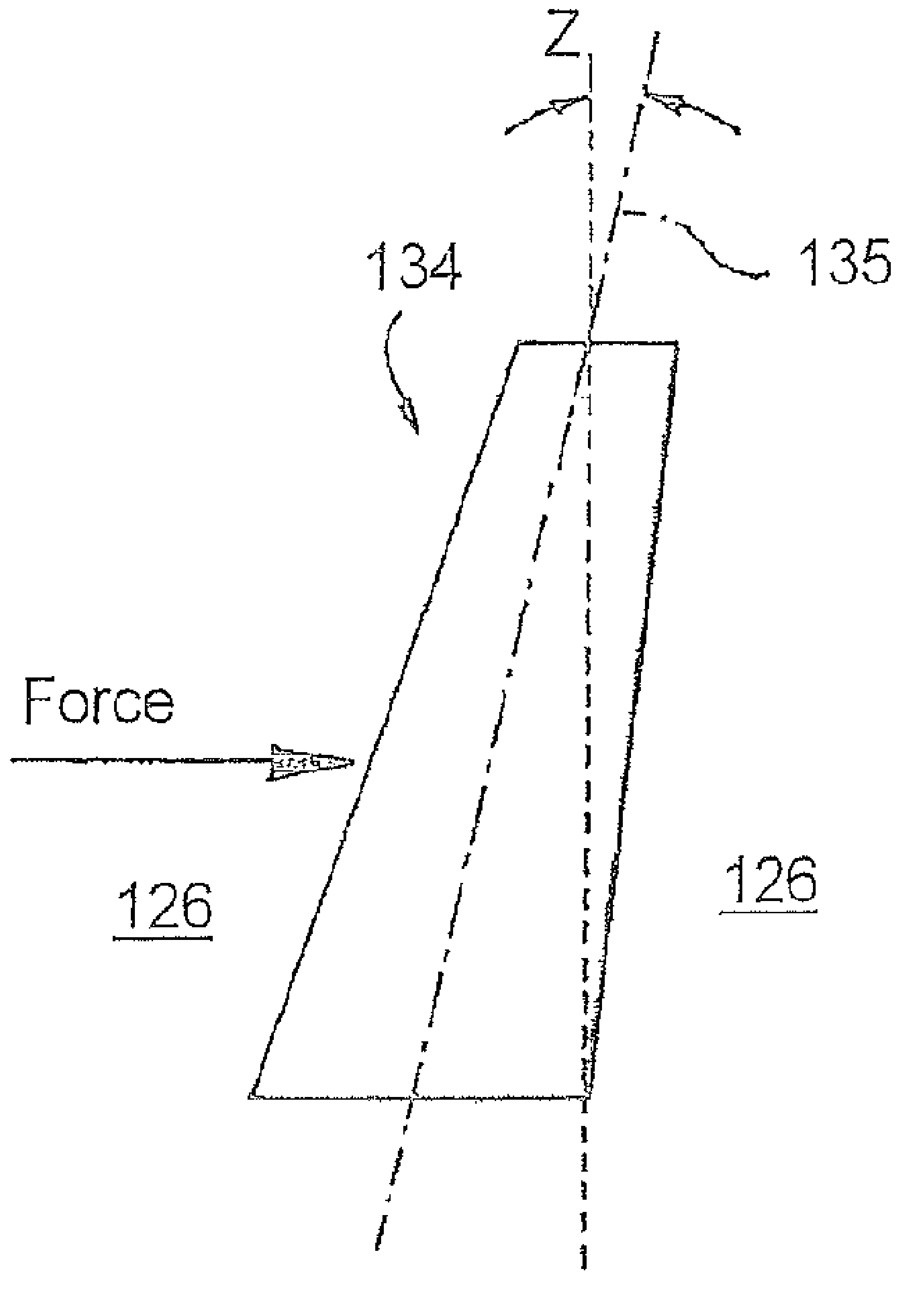


Fig. 8

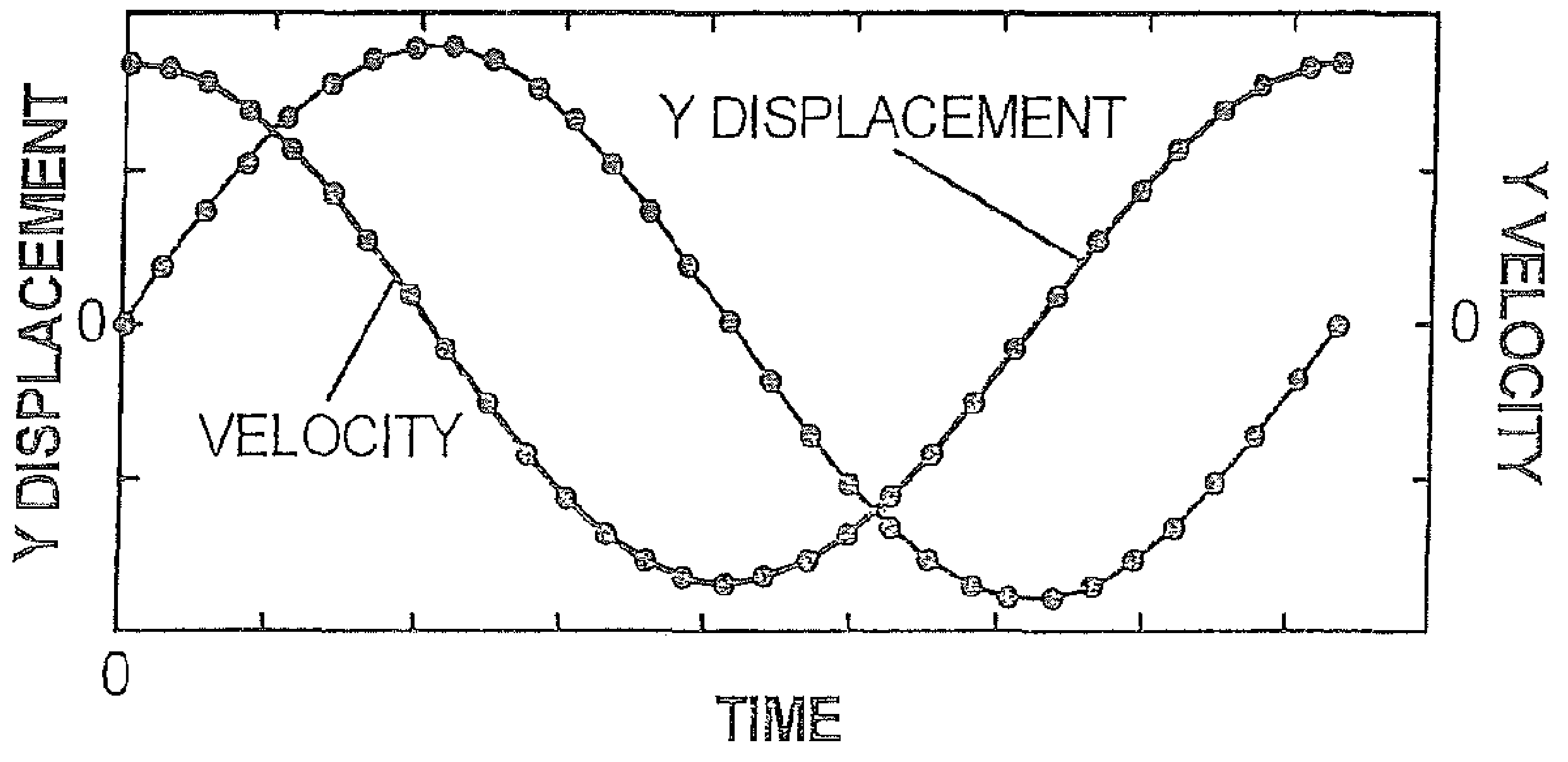


Fig. 9

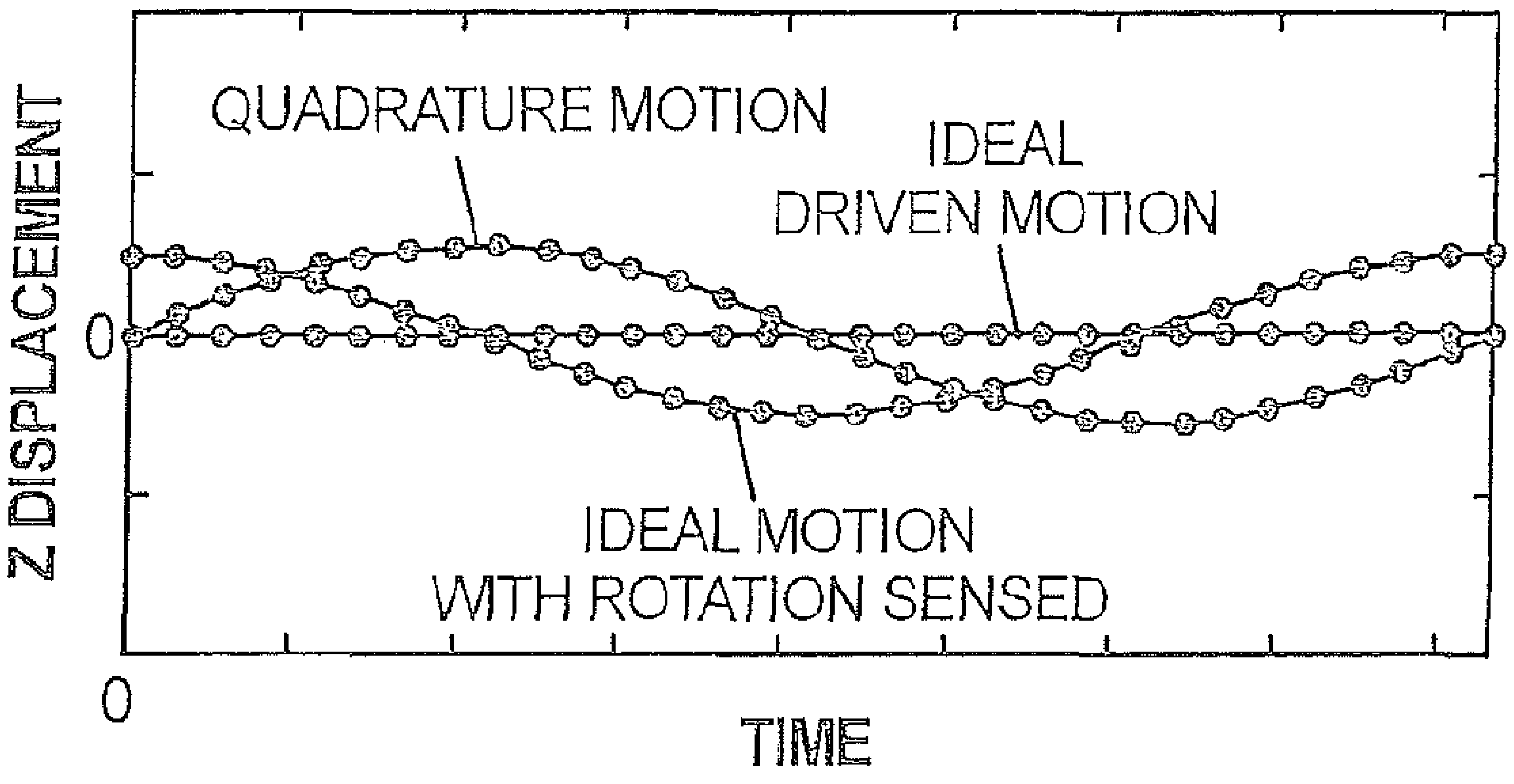


Fig. 10

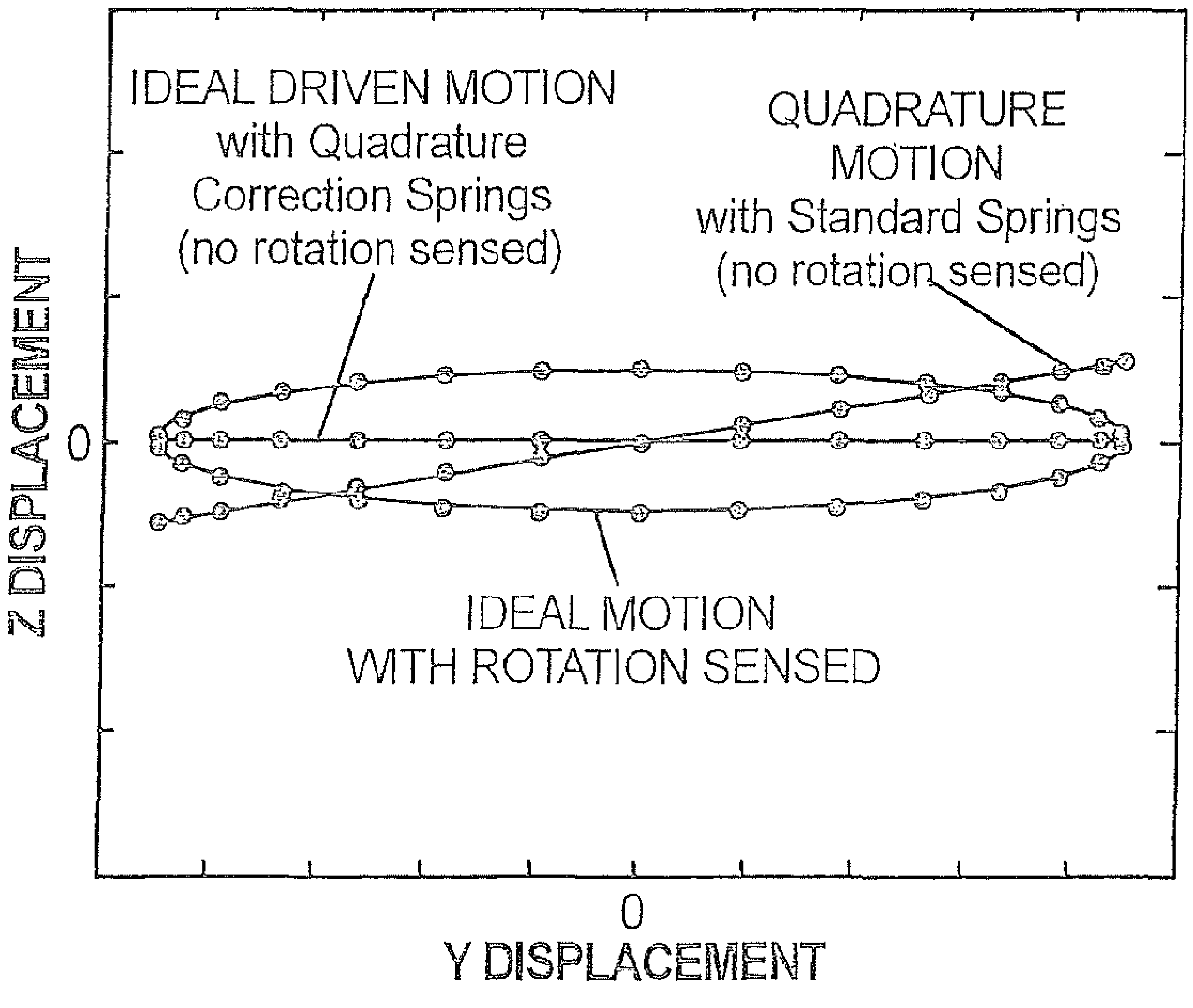
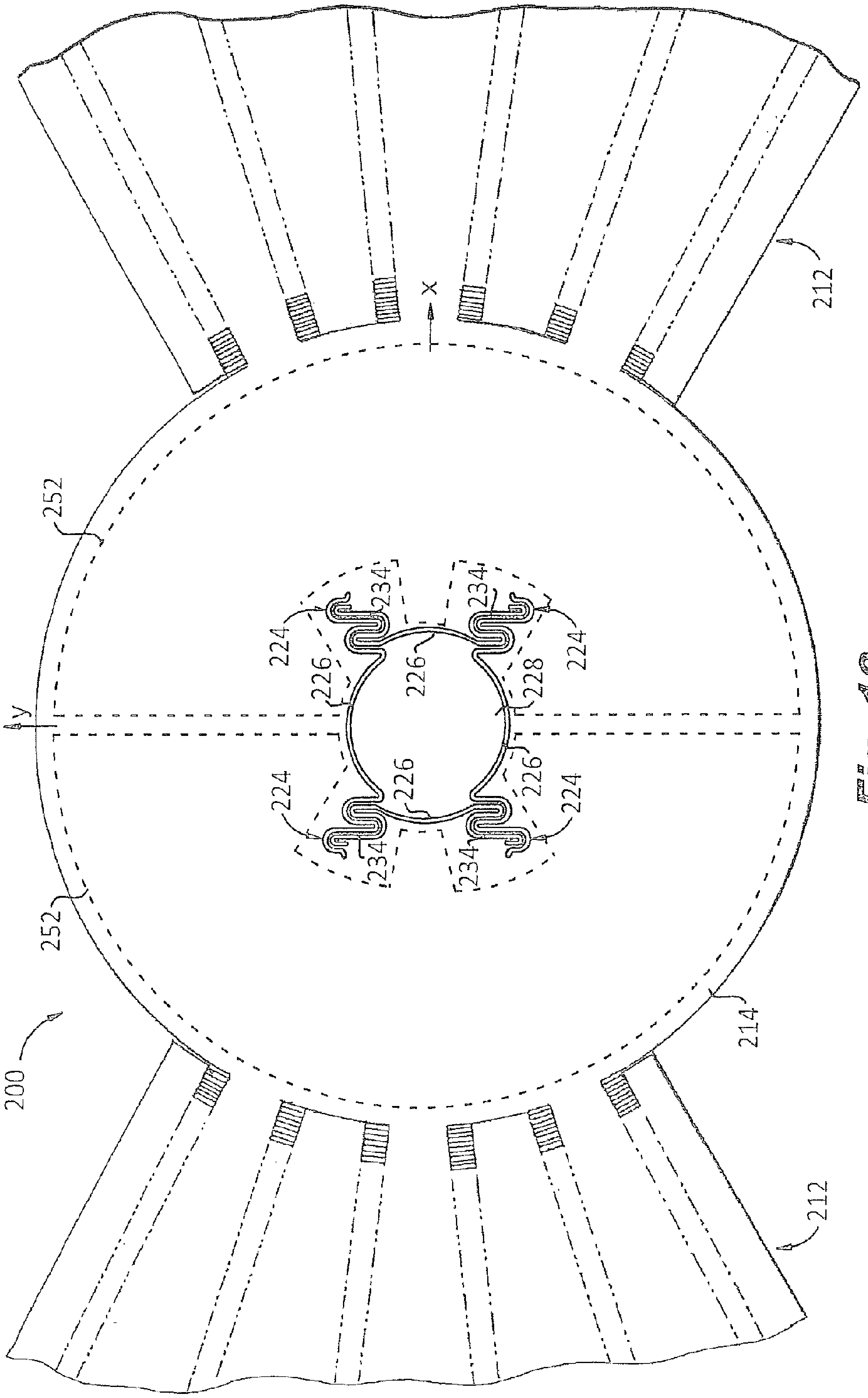


Fig. 11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200
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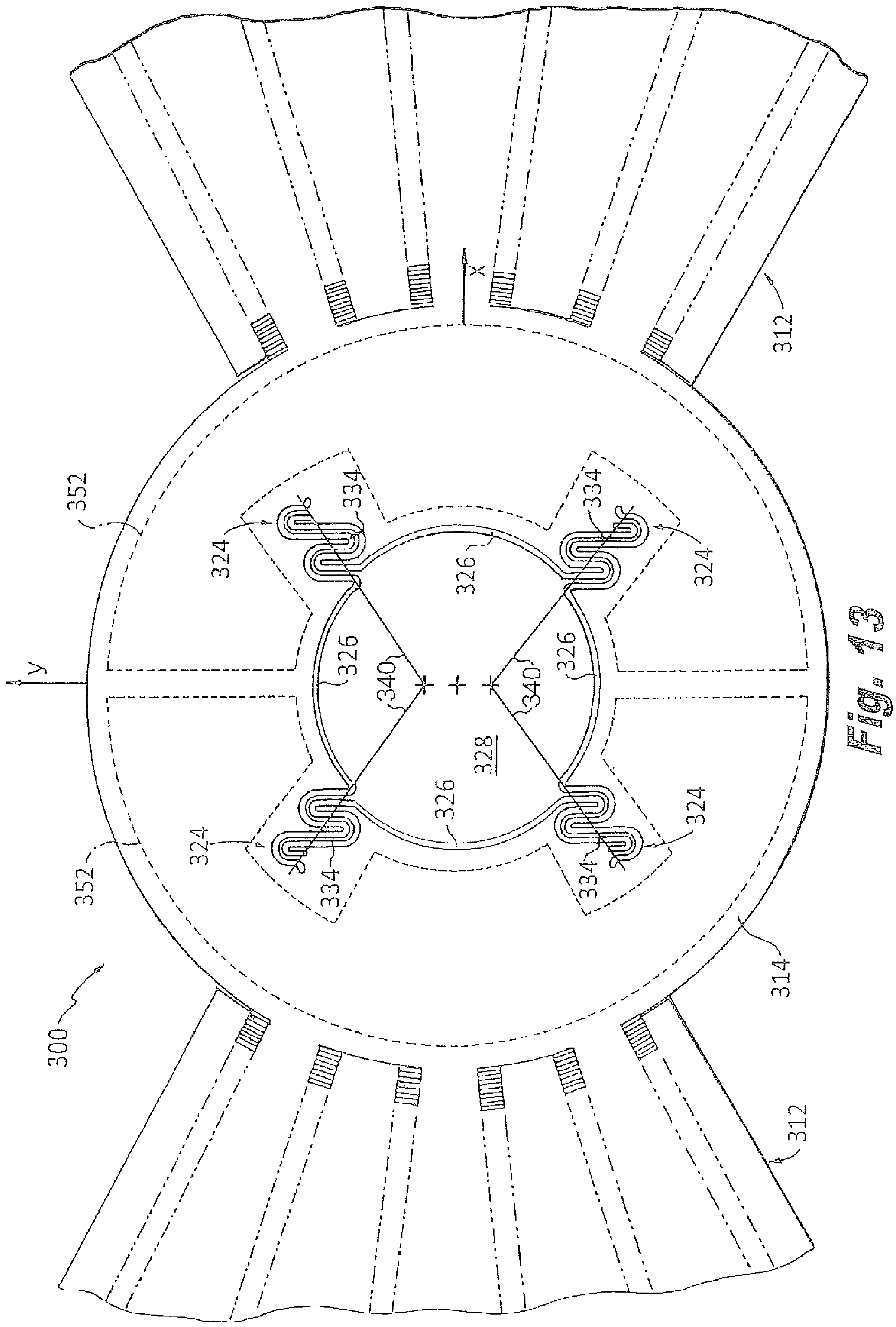
Fig. 12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340
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326
324
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334
334
352
314
300
312
y

Fig. 13

MEMS GYROS WITH QUADRATURE REDUCING SPRINGS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional of copending application U.S. Ser. No. 12/911,504, filed on Oct. 25, 2010, the entire contents of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to spring set configurations for microelectromechanical systems (MEMS) devices, and more particularly to spring set configurations for MEMS gyros.

2. Description of Related Art

A variety of gyroscope devices are known for providing navigational guidance such as in aerospace applications. Microelectromechanical systems gyroscopes (hereinafter MEMS gyros) are known for their compact size and relatively low cost of manufacture. In addition to aerospace applications, the small size and low cost of MEMS gyros lends them well to a variety of other applications including motion sensing for image stabilization and input devices, for example.

Gyros operate by moving a mass. When the mass is located in a rotating reference frame, for example, it will be subjected to a Coriolis force calculated by the formula:

$$F_c=2mv\times\Omega,$$

where F_c is the Coriolis force, m is the mass of the moving body, v is the velocity vector for the rotating body, and Ω is the angular velocity vector for the rotating body. Conventional spinning mass gyros generate large Coriolis forces by spinning at high velocities. MEMS gyros typically do not have bearings on which they can continually spin. Instead, MEMS microstructures create motion by vibrating a mass. When the mass is vibrated at its natural frequency, large amplitudes can be achieved with minimal excitation. When this driven mode is excited in a rotating reference frame, the resulting Coriolis force will be perpendicular to the driven mode direction due to the cross product of the velocity and angular velocity vectors in the formula above. This motion in the perpendicular direction is what is sensed to determine rotational rate of the reference frame. The mass is driven at its drive resonance frequency, thus the sensed motion will also vibrate at the same frequency but in an orthogonal direction. If the microstructure is designed such that the sensed motion natural frequency is close to the driven frequency, the resulting motion will be gained dynamically. The amount of this dynamic gain (Q) can be described by

$$Q=\omega_{drive}/\Delta\omega,$$

where ω_{drive} is the driven frequency and Δω is the difference in frequency between the driven and sensed modes. The motion can be sensed and driven capacitively.

Δω is a key parameter for resonant gyros. The smaller the value of Δω, the greater the gain. But this increased gain comes at a cost in the form of decreased bandwidth of rotation that can be detected. Since Δω is the difference between the sense and drive frequencies, small variations in these nominal frequencies can cause relatively large fluctuations in Δω. Therefore, consideration must be made to ensure that process variations affect both sense and drive frequencies in the same or similar amounts.

A typical example of such a MEMS gyro includes a microstructure that is driven in-plane, oscillating about the z-axis. If the reference frame is rotated about the x or y-axis, Coriolis motion will be produced about the y or x-axis, respectively. Such a gyro can be optimized to sense reference frame rotations about only one axis, for example the x-axis. This is achieved by placing the majority of the mass close to the x-axis and as far from the y-axis as possible. This minimizes the moment of inertia about the x-axis and maximizes the moment of inertia about the y-axis. This also makes the lowest resonant mode the desired y-axis rotation. Electrodes with opposite polarity (high and low bias) are placed under the microstructure on either side of the y-axis so when the capacitance is changed a current is generated that can be converted to a voltage with a charge amplifier. If the microstructure were to rotate about the x-axis, there would be no net current generated because both capacitances would change equally.

In ideal operation, a point "p" on the end of the drive motor will move back and forth in the y-direction as the gyro is driven. If the reference frame is not rotating, the point p will only move in the y-direction and will not move in the z-direction. When the reference frame rotates about the x-axis, a Coriolis force is generated proportional to the velocity in the z-direction according to the formula for calculating F_c above. The motion generated is proportional to the Coriolis force.

Quadrature motion is generated when point p moves in the z-direction in its driven mode. This results in a driven motion that is 90 degrees out of phase with the rate rotation sense signal. The signal from the gyro is sinusoidal at the driven frequency with phase components from both the desired rotation rate signal and from the quadrature. The two phases of the signal are decoupled by a demodulation circuit. The demodulation circuit provides an output signal that includes an average amplitude of the in-phase rate signal as well as the out of phase quadrature signal. The in-phase rate signal is the desired output signal the gyro is designed to sense.

When an unwanted quadrature signal is too large, it can cause the charge amplifier to clip and any information of the desired rate signal is clipped along with it. Electrical mitigation circuits have been utilized to reduce this effect of quadrature error on the desired rate signal. Typical quadrature error mitigation circuits work by applying both high and low bias voltages on compensation electrodes. This generates a current with the in-plane driven motion having the same phase as the unwanted quadrature. By applying a compensation voltage bias, the quadrature mitigation circuit can minimize the unwanted quadrature signal. The amount of compensation voltage bias needed to minimize the unwanted quadrature signal is an indicator of how far the microstructure is tipping out of plane. Design improvement can be measured by how much compensation voltage is reduced. The quadrature error mitigation circuit is limited by the available voltage. It is not uncommon for quadrature error to be so large that it cannot be corrected with a quadrature error mitigation circuit. Some gyro designs have larger compensation electrodes so that more current can be generated and larger quadrature error signals can be minimized. Larger compensation voltages may result in unacceptable noise levels in the device. Minimizing unwanted quadrature by electrical means can make the microstructure useable, but high level performance characteristics such as Allan variance and temperature sensitivity may be compromised since they have been correlated to compensation voltage levels, probably due to the microstructure moving out of plane.

A primary cause of quadrature error is the etch angle variation in the microstructure components, and particularly in the springs. An ideal orthogonal spring will move in the direction it is forced, but when there is an etch angle producing an angled neutral axis (for instance a parallelogram cross-section), i.e., a tilt of some degree, the spring will also move out of plane to the forcing direction.

Deep reactive-ion etching (DRIE) tools are state of the art tools typically used to construct MEMS devices. DRIE tools use etch chemistry in a directional plasma to etch silicon vertically. These tools can have a radial center-to-edge variation in etched angle due to edge effects of the plasma. The orientation of the etch angle can be dependent on where the die is located on the wafer with the straightest edges (least tilt) being produceable only in a correlated portion of the wafer.

The driven mode is affected by both the orientation and magnitude of the etch angle. When the etch angle direction is orthogonal to the spring direction, it maximizes the out of plane component of motion. When the etch angle direction is the same as the spring direction, there is little effect. When an etch angle is present on the gyro in the y-direction, the out of plane component is generated by the spring component in the x-direction, and this causes a rotation about the y-axis. The opposite is true for etch angles in the y-axis in that they generate an out of plane motion about the x-axis. Only out of plane motions about the y-axis produce a signal, and thus quadrature, as described above.

The magnitude of quadrature displacement is affected by the differences in natural frequencies of the quadrature mode and the driven mode. In the same way that the gyro output is gained dynamically due to the sense mode being close to the driven mode, the quadrature motion is also gained. X-direction etch angles cause out of plane motion about the x-axis. Since this mode is far from the driven frequency, there is not much dynamic gain present. This motion does not generate an electrical current since the out of plane capacitors change equally. However, y-direction etch angles cause out of plane motion about the y-axis. This mode is intentionally close to driven mode because it is needed to amplify the desired Coriolis motion. Consequently, the quadrature motion about the y-axis is amplified by its dynamic gain (Q), and its motion produces an electrical quadrature signal.

Such conventional methods and systems have generally been considered satisfactory for their intended purpose. However, there is still a need in the art for spring set configurations on MEMS devices and particularly on MEMS gyros that allow for reduced sensitivity to etch angle errors (or inaccuracies) due to processing variations. There also remains a need in the art for such MEMS devices and MEMS gyros that are easy to make and use. The present invention provides a solution for these problems.

SUMMARY OF THE INVENTION

The subject invention is directed to new and useful spring set configurations for MEMS devices, and in particular MEMS gyros for sensing rotation. A MEMS gyro includes a drive motor defining orthogonal x, y, and z-axes. In certain embodiments, the drive motor is configured to oscillate a suspended drive mass around the z-axis with oscillating motion substantially in a plane with the x and y-axes. A plurality of drive springs connect the suspended drive mass to an intermediate suspended mass concentric with the suspended drive mass. Each drive spring has a spring element anchored to the intermediate suspended mass at a first anchor point and anchored to the suspended drive mass at a second anchor point. The first and second anchor points are located on a respective off-axis common radius originating at the z-axis, meaning that the common radius is not oriented along the x or y-axes.

In certain embodiments, the MEMS gyro further includes a pedestal mass connected to an underlying substrate. The pedestal mass and intermediate suspended mass are connected by a plurality of anchor springs. Each anchor spring has a spring element anchored to the intermediate suspended mass at a first anchor point and anchored to the pedestal mass at a second anchor point. It is also contemplated that at least one of the first and second anchor points of each anchor spring can be located on an off-axis common radius originating at the z-axis with the first and second anchor points of a respective one of the drive springs. For example, the second anchor point of each anchor spring can be located on the common off-axis radius. It is contemplated that the intermediate suspended mass can be located radially inward of the suspended drive mass, and that the pedestal mass can be located radially inward of the intermediate suspended mass. However, any other suitable ordering of the masses or additional masses can be used without departing from the spirit and scope of the invention. For example, the pedestal mass can be radially outward of the intermediate suspended mass, which can be radially outward of the suspended drive mass. Additionally, it is contemplated that a MEMS device having a single mass connected to a substrate by a set of advantageously configured springs may be used without departing from the spirit and scope of the invention.

It is contemplated that the anchor springs can be predominantly compliant in rotation about the y-axis and resistant to motion in all other directions. The drive springs can similarly be predominantly compliant in rotation about the z-axis and resistant to motion in all other directions.

In certain embodiments, the suspended drive mass and the intermediate suspended mass are separated by a plurality of trenches, which can have a substantially constant width. The spring element of each drive spring can have a width greater than that of the spring element of each anchor spring. The anchor springs can be predominantly curved and the drive springs can be predominantly straight. The mass of each spring element can be advantageously distributed substantially equally across the respective off-axis common radius of the first and second anchor points thereof to reduce off-axis sensitivities. It is also contemplated that the length of each spring element can be distributed substantially equally across the respective off-axis common radius.

The invention also provides a spring set for a MEMS device wherein the spring element of each drive spring is predominantly oriented parallel to the y-axis. It is contemplated that the spring element of each drive spring can include a plurality of straight sections each oriented substantially parallel to the y-axis.

The invention also provides a spring set configuration for a MEMS device wherein each spring has a spring element with a cross-section having an etch angle that is in line or oblique with respect to the z-axis. The springs can impart a characteristic quadrature error, or out of plane motion, to the suspended mass or masses due to variations in etch angle. It is contemplated that the quadrature error due to process variations in the etch angle of springs which are in line or oblique with respect to the z-axis can be reduced by a factor of about 5 times or greater compared with traditional spring set configurations having similar process variations in etch angle. It is also contemplated that the characteristic quadrature error or out of plane motion can be substantially insensitive to process induced etch angle variation in the spring elements.

It is contemplated that in certain embodiments, the cross-section of each spring element is substantially in the shape of a parallelogram. It is also contemplated that the cross-section of each spring element can be substantially in the shape of a trapezoid with two parallel edges orthogonal to the z-axis and with two oblique edges oblique with respect to the z-axis. The average angle of each of the two oblique edges can be oblique with respect to the z-axis. It is also contemplated that the cross-section of each spring element can be any arbitrary shape with a parallel or an oblique neutral axis with respect to the z-axis.

The invention also provides a spring set for a MEMS device, including a plurality of springs connecting a first mass to a seconds mass. In certain embodiments, each spring has a spring element anchored to the first mass at a first anchor point and anchored to the second mass at a second anchor point. The first and second anchor points of each spring element are located on a respective common vector that is oblique with respect to orthogonal x and y-axes defined by the first and second masses. Each spring can have a mass and/or length that is balanced about the respective common vector. In accordance with certain embodiments, each spring has a spring element predominantly oriented parallel to a common y-axis. It is also contemplated that in certain embodiments, the first mass defines a plane of motion. Each drive spring includes a spring element with a cross-section having a process induced etch angle that is oblique with respect to a z-axis orthogonal to the plane of motion. The drive springs impart a characteristic component of motion out of the plane of motion to the second mass that is substantially insensitive to variation in the process induced etch angle of the spring elements. It is also contemplated that the first or second mass may be the substrate when applied to a MEMS process.

It is contemplated that one or more additional masses can each be connected to another one of the masses by a respective plurality of springs. The plurality of springs can be arranged with quarter symmetry about a z-axis that is orthogonal to the axes or plane of the first body.

These and other features of the systems and methods of the subject invention will become more readily apparent to those skilled in the art from the following detailed description of the preferred embodiments taken in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

So that those skilled in the art to which the subject invention appertains will readily understand how to make and use the devices and methods of the subject invention without undue experimentation, preferred embodiments thereof will be described in detail herein below with reference to certain figures, wherein:

FIG. **1**A is a plan view of an exemplary MEMS gyro typical of the prior art exhibiting a set of springs that result in typical high sensitivity to quadrature error, showing the drive mass connected to the intermediate suspended mass by four drive springs and a central pedestal mass connected to the intermediate suspended mass by four anchor springs;

FIG. **1**B is a plan view of another exemplary MEMS gyro typical of the prior art exhibiting a set of springs that result in typical high sensitivity to quadrature error, showing the drive mass connected to the pedestal by a spring set with four springs;

FIG. **2** is a perspective schematic view of an exemplary embodiment of a MEMS gyro constructed in accordance with the present invention, showing the orientation of the spring set of the invention, the drive mass, suspended intermediate mass, and pedestal with respect to the x-, y-, and z-axes;

FIG. **3** is a plan view of a portion of the MEMS gyro of FIG. **2**, showing the four drive springs aligned with the y-axis;

FIG. **4** is an enlarged plan view of a the portion of the MEMS gyro indicated in FIG. **3**, showing the alignment of spring anchor points along an off-axis common radius originating at the z-axes;

FIGS. **5-7** are cross-sectional elevation views of portions of MEMS device spring elements constructed in accordance with the subject invention, showing different etch angles arising from process variations, wherein each cross-section is in the shape of a parallelogram;

FIG. **8** is a cross-sectional elevation view of a portion of a MEMS device spring element constructed in accordance with the subject invention, showing a trapezoidal cross-section in which two different etch angles are present on opposite sides of the spring element, and wherein the average etch angle is itself oblique with respect to the z-axis;

FIG. **9** is a plot showing velocity and displacement in the y-direction as a function of time for a point P on an ideal MEMS gyro;

FIG. **10** is a plot showing displacement in the z-direction as a function of time for a point P on an ideal MEMS gyro, also showing the ideal z-direction displacement with rotation sensed, and showing typical z-direction displacement with quadrature motion;

FIG. **11** is a plot showing displacement in the z and y-directions for a point P under ideal driven motion, ideal sensed motion, and driven motion with quadrature;

FIG. **12** is a plan view of another exemplary MEMS gyro constructed in accordance with the subject invention, showing a configuration with only one moving mass and only one spring set; and

FIG. **13** is a plan view of another exemplary MEMS gyro constructed in accordance with the subject invention, showing a configuration in which the anchor points of each spring element lie on a common vector that is not a radius passing through the z-axis, and that is not parallel or orthogonal to the x and y-axes.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Reference will now be made to the drawings wherein like reference numerals identify similar structural features or aspects of the subject invention. For purposes of explanation and illustration, and not limitation, a partial view of an exemplary embodiment of a spring set configuration used on a MEMS gyro in accordance with the invention is shown in FIG. **2** and is designated generally by reference character **100**. Other embodiments of spring set configurations used on MEMS gyros in accordance with the invention, or aspects thereof, are provided in FIGS. **3-13**, as will be described. The systems and methods of the invention can be used reduce quadrature error in MEMS devices, and more particularly in MEMS gyros.

With reference to FIG. **1**A, a portion of a prior art MEMS gyro **10** is shown in plan view. MEMS gyro **10** includes an opposed pair of comb drives **12**. A drive mass **14** includes driven portions **16** that form part of comb drives **12**, with intermeshing portions **18** formed between stationary portions **20** of comb drives **12** and driven portions **16**. When oscillating electrical charges are applied across intermeshing portions **18**, oscillating motion is imparted to drive mass **14** in the direction indicated in FIG. **1**A by double arrows. This oscillating motion is rotation about the z-axis, which is oriented into and out of the view plain of FIG. **1**A (see FIG. **2** for a perspective view of a z-axis).

Inboard of drive mass **14** is an intermediate suspended mass **22** that is connected to drive mass **14** by four drive springs **24** formed by etching trenches **26** between drive mass **14** and intermediate suspended mass **22**. Inboard of intermediate suspended mass **22** is a pedestal mass **28** that is anchored to the underlying substrate and is connected to intermediate suspended mass **22** by anchor springs **30** formed by etching trenches **32** between pedestal mass **28** and intermediate suspended mass **22**. Drive springs **24**, anchor springs **30**, intermediate suspended mass **22**, and drive mass **14** are dimensioned to achieve the desired out of plane resonant frequency. Drive springs **24** and drive mass **14** are dimensioned to achieve the desired in plane (drive) resonant frequency. Comb drives **12** operate at this natural frequency to maintain the desired in plane driven motion.

While comb drives **12** are imparting rotational motion on drive mass **14**, rotation of the reference frame will give rise to a Coriolis force, tending to rotate both drive mass **14** and intermediate suspended mass **22** out of plane, in a direction orthogonal to both the driven motion and the reference frame rotation. Capacitor plates **29** mounted proximal to (above or beneath) intermediate suspended mass **22** and/or drive mass **14** (indicated by broken lines in FIG. **1**A) make it possible to sense the out of plane displacement of intermediate suspended mass **22** and/or drive mass **14**, and thereby sense rotation of the reference frame.

With continued reference to FIG. **1**A, the mass of drive mass **14** is distributed as close to the x-axis (the sense axis) and as far from the y-axis (the non-sensing axis) as possible. This distribution desensitizes MEMS gyro **10** to reference frame rotation about the non-sensing y-axis and sensitizes it to reference frame rotation about the desired x-axis. It is desirable for MEMS gyros to be particularly sensitive to motion in only one axis so that motion in multiple directions can be resolved using separate MEMS gyros. For example, using three MEMS gyros **10** oriented orthogonal to one another, it is possible to resolve magnitude and direction of reference frame rotation in any arbitrary direction by sensing x, y, and z-components of rotation on the individual MEMS gyros.

Ideally, when MEMS gyro **10** is operating without reference frame rotation, drive mass **14** will oscillate in plane with the rest of MEMS gyro **10**. This direction of motion is called the driven mode and is represented in FIG. **9** by the y displacement and velocity curves and in FIGS. **10** and **11** by the flat lines at zero z-displacement. However, in practice the formation of trenches **26** and **32**, such as by state of the art DRIE etching techniques, is imperfect. Rather than forming trenches that are perfectly vertical with respect to the plane of MEMS gyro **10**, known etching processes have variation that may impart an undesirable etch angle. The result is that the spring elements of drive springs **24** and anchor springs **30**, when viewed in cross-section, are not rectangular as shown in FIG. **6**, but are instead non-ideal shapes such as parallelograms or trapezoids as indicated in FIGS. **5**, **7**, and **8**.

Since the cross-sections of drive springs **24** and anchor springs **30** are not ideal vertically oriented rectangles, drive springs **24** and anchor springs **30** cause out of plane motion giving rise to quadrature error as described above. This undesired quadrature motion is represented in FIG. **10** by the quadrature motion curve and in FIG. **11** by the angled quadrature motion line. FIG. **10** shows the quadrature motion curve is 90 degrees out of phase with the ideal motion with rotation sensed curve.

Ideally, when MEMS gyro **10** operates in a rotating reference frame, the Coriolis force on drive mass **14** causes it to oscillate out of plane, in what is called the sense mode. This ideal sense mode motion is represented in FIGS. **10** and **11** by the curves indicated for ideal motion with rotation sensed. However, in practice the quadrature error upsets this ideal motion, causing an extra out of phase signal which corrupts the desired signal.

With reference now to FIG. **1**B, another exemplary MEMS gyro **60** typical of the prior art is shown, having another spring set configuration that results in typical high sensitivity to quadrature error. MEMS gyro **60** includes an opposed pair of comb drives **62**, drive mass **64** including driven portions **66** that form part of comb drives **62**, with intermeshing portions **68** formed between stationary portions **70** of comb drives **62** and driven portions **66**, much as described above with respect to MEMS gyro **10**. Unlike MEMS gyro **10** described above, MEMS gyro **60** does not include an intermediate suspended mass. Rather, MEMS gyro **60** includes a single driven mass, namely drive mass **64**, which is connected directly to pedestal **78** mass by a spring set with four springs **74**. Springs **74** are formed by removal of material from trenches **75**. Capacitor plates **79** operate much as capacitor plates **29** described above. Even without an intermediate suspended mass, etch angle variation in forming springs **74** causes out of plane motion on the single drive mass **64** resulting in quadrature error, much as described above with respect to MEMS gyro **10**.

Referring now to FIG. **2**, the subject invention is directed to new and useful configurations of spring sets on MEMS devices, particularly MEMS gyros for sensing rotation, such as MEMS gyro **100**. MEMS gyro **100**, depicted in reference to orthogonal x, y, and z axes, includes a drive motor in the form of opposed comb drives **112**, with driven portions, intermeshing portions, and stationary portions like those of comb drives **12** described above. Comb drives **112** are configured to oscillate suspended drive mass **114** around the z-axis with oscillating motion substantially in a plane with the x and y-axes when there is no reference frame rotation. Four drive springs **124** connect suspended drive mass **114** to an intermediate suspended mass **122** that is concentric and substantially in plane with suspended drive mass **114**.

Referring now to FIGS. **3** and **4**, each drive spring **124** is anchored to intermediate suspended mass **122** at a first anchor point **136** and anchored to suspended drive mass **114** at a second anchor point **138**. The first and second anchor points **136**, **138** are located on a respective common radius **140** originating at the z-axis. This alignment makes drive springs **124** compliant to rotation motion about the z-axis, i.e., the drive mode, and makes them resistant to motion in all other directions including translation.

MEMS gyro **100** further includes a pedestal mass **128** connected to an underlying substrate. Pedestal mass **128** and intermediate suspended mass **122** are connected by four anchor springs **130**. Each anchor spring **130** is anchored to intermediate suspended mass **122** at a first anchor point **144** and anchored to pedestal mass **128** at a second anchor point **146**. Anchor point **146** of each anchor spring **130** is located on the off-axis common radius **140** with the first and second anchor points **136**, **138** of a respective drive spring **124**, meaning that common radius **140** is not oriented along the x or y-axis. It is also possible to configured the anchor springs with anchor point **144** located on the common radius **140** with the first and second anchor points **136**, **138** of a respective drive spring **124**. It is also possible to configure the anchor springs with both anchor points thereof located on the respective off-axis common radius without departing from the spirit and scope of the invention. Anchor springs **130** are formed between trenches **132** similar to and simultaneously with trenches **126** of drive springs **124**. The shape and placement of anchor springs **130** make them compliant to rotational motion about the y-axis, i.e., the sense mode, and makes them resistant to motion in other directions.

Suspended drive mass **114** and intermediate suspended mass **122** are separated by a plurality of trenches **126**, which have a substantially constant width. Constant width trenches minimize DRIE etch variation, for example, by introducing equal amounts of exposed silicon around key features during etching. Those skilled in the art will readily appreciate that other configurations having variable trench widths are also possible without departing from the spirit and scope of the invention. Spring element **134** of each drive spring **124** has a width greater than the width of spring elements **142** of anchor springs **130**. However, those skilled in the art will readily appreciate that other configurations wherein the drive springs and anchor springs are the same size, or wherein the anchor springs are wider than the drive springs, are also possible without departing from the spirit and scope of the invention.

Anchor springs **130** are predominantly curved, whereas drive springs **124** are predominantly straight. Each spring element **134** of drive spring **124** has four straight sections **148** connected in series by three semi-circular curved sections **150**. Those skilled in the art will readily appreciate that any suitable number of straight sections and curved sections can be used without departing from the spirit and scope of the invention. The straight sections **148** of each drive spring **124**, which predominate the length of spring elements **134**, are aligned parallel with the y-axis. Y-axis oriented drive springs **124** reduce unwanted quadrature motion derived from non-orthogonal spring etch angles due to process variation. FIG. **3** shows all four drive springs **124** aligned with the y-axis. The length and mass of each spring element **134** is advantageously distributed substantially equally across the respective common radius **140**. This balance reduces off-axis sensitivities.

Referring now to FIGS. **5**-**8**, exemplary cross-sections of spring elements **134** are shown, which can arise due to process variations when manufacturing MEMS gyros. FIG. **6** shows the design ideal, in which the etch angles of both trenches **126** defining spring element **134** are vertical, i.e., aligned to the z-axis, which is parallel to the z-axis shown in FIG. **2**. FIGS. **5** and **7** show cross-sections of spring element **134** having parallelogram shapes where the etch angle of trenches **126** of spring element **134** are angled clockwise and counter-clockwise relative to the z-axis, respectively, due to unwanted process induced etch angle variations. FIG. **8** shows spring element **134** with a trapezoidal cross-section with trenches **126** on two different angles with respect to the z-axis. The average angle **135** of the two trenches **126** is itself oblique with respect to the z-axis. Unwanted process variations change the etch angle from the designed ideal and can result in undesired quadrature error, regardless of the designed ideal etch angle. Those skilled in the art will readily appreciate that process induced etch angle variation can be mitigated with the spring configurations described above regardless of the designed etch angle of a spring element with respect to the z-axis, without departing from the spirit and scope of the invention.

The same basic trench angle variation that may occur on drive springs **124** also applies to anchor springs **130**. Variation in line widths causes the sense mode stiffness and driven mode stiffness to change differently, which causes significant variation in the key $\Delta\omega$ parameter. Utilizing two sets of springs, e.g. drive springs **124** and anchor springs **130** helps assure that the driven and sense modes track properly. Drive springs **124** determine the driven mode stiffness while both drive springs **124** and anchor springs **130** define the sense mode stiffness. Anchor springs **130** have a smaller width than drive springs **124** and are curved to make them more sensitive to line width variation, such that both driven and sense modes have the same sensitivity to line width variation. Thus anchor springs **130** and drive springs **124** are tuned together to reduce $\Delta\omega$ variation.

Exemplary design parameters for MEMS gyro **100** include driven and sense modes having the lowest resonant modes at around 6 KHz, tight tracking of $\Delta\omega$ around 150 Hz, and high resonant frequencies of all other modes at greater than around 7.5 KHz. Those skilled in the art will readily appreciate that other suitable configurations can be practiced for specific applications without departing from the sprit and scope of the invention.

Due to their combination of geometries, spring elements having curved and straight sections, orientation of spring element anchor points with respect to the off-axis common radius, orientation of spring element segments with respect to a specific axis, balance of the length of spring elements about the off-axis common radius, and mass balance of spring elements about the off-axis common radius, drive springs **124** and anchor springs **130** impart a characteristic quadrature error mitigation to drive mass **114** that renders the output substantially insensitive to the process-induced etch angle variations of drive springs **124** and anchor springs **130**, while maintaining the desired resonant modes. Therefore, MEMS gyro **100** results in consistently low quadrature error even with process variations in manufacturing causing undesirable etch angles. It is estimated that the quadrature error due to process variations in the etch angle in MEMS gyro **100** can be reduced by a factor of about 5 times or greater compared with a MEMS gyro employing traditional spring set configurations having similar process variations in etch angle. MEMS gyro **100** has a reduced quadrature error regardless of whether the cross-section of its drive springs **124** and/or anchor springs **130** are parallelogram shaped, trapezoid shaped, or any other shape with angled neutral axis.

Just as the described spring configuration reduces quadrature error, an intentional out of plane signal can be advantageously magnified. This can be used to intentionally induce out of plane motion.

Capacitor plates **152** are mounted under drive mass **114** as shown in FIG. **2**. Those skilled in the art will readily appreciate that capacitor plates can be mounted proximal to (above or beneath) the top and/or bottom of intermediate suspended mass **122** and/or drive mass **114**, without departing from the spirit and scope of the invention, since both intermediate suspended mass **122** and drive mass **114** can move out of plane in the presence of reference frame rotation. Those skilled in the art will readily appreciate that any suitable capacitor location can be used, or any other type of sensor besides capacitor type sensors can be used without departing from the spirit and scope of the invention.

As described above, intermediate suspended mass **122** is located radially inward of suspended drive mass **114**, and pedestal mass **128** is located radially inward of intermediate suspended mass **122**. However, those skilled in the art will readily appreciate that any other suitable configuration or ordering of the masses can be used without departing from the spirit and scope of the invention. For example, the pedestal mass can be radially outward of the intermediate suspended mass, which can be radially outward of the suspended drive mass. While described herein with the exemplary configuration having four each of drive springs and anchor springs, those skilled in the art will readily appreciate that any suitable number of drive or anchor springs can be used without departing from the spirit and scope of the invention. While described herein with the exemplary configuration having two suspended masses (intermediate suspended mass **122** and suspended drive mass **114**), those skilled in the art will readily appreciate that any suitable number of suspended masses, including a single suspended mass or multiple suspended masses, can be used without departing from the spirit and scope of the invention. Similarly, those skilled in the art will readily appreciate that any suitable number of spring sets connecting masses to each other or to a substrate can be used without departing from the spirit and scope of the invention.

Compensation electrode authority can advantageously be combined with the features of drive springs **124** and anchor springs **130** to further reduce quadrature error. If used, the compensation electrode authority, or any other suitable means of electrically reducing quadrature error, should have enough authority to minimize expected quadrature error, but not so much that it adds a parasitic capacitance noise source.

Referring now to FIG. **12**, another exemplary embodiment of a MEMS gyro **200** is shown, in which there is no intermediate suspended mass. MEMS gyro **200** includes comb drives **212**, drive mass **214**, capacitor plates **252**, pedestal mass **228**, springs **224**, trenches **226**, and spring elements **234** much as described above with respect to MEMS gyro **100**. With a single driven mass, namely drive mass **214**, connected by a single set of springs **224** directly to pedestal mass **228**, Coriolis forces can act on drive mass **214** as it oscillates about pedestal mass **228**, moving capacitor plates **252** in the sense mode direction. Pedestal mass **228** can be part of or connected to the underlying substrate. The characteristics of springs **224**, just as springs **124** described above, reduce sensitivity to etch process variation, e.g., reducing quadrature error. In applications where a certain component of out of plane motion is desired, springs **224** reduce process variation induced deviations from the desired out of plane motion, much like springs **124** above.

Spring elements **234** of springs **224** have anchor points (not shown in FIG. **12**, but see, e.g., FIG. **4**) that lie on a common off-axis radius for each spring **224**, with respect to the x and y-axes. However, it is not necessary for the anchor points to lie on a radius. Referring now to FIG. **13**, another exemplary embodiment of a MEMS gyro **300** is shown in which the anchor points do not lie on radii of the MEMS gyro. MEMS gyro **300** includes comb drives **312**, drive mass **314**, capacitor plates **352**, pedestal mass **328**, springs **324**, trenches **326**, and spring elements **334** much as described above with respect to MEMS gyro **200**. The anchor points of each spring **334** lie on a vector **340** that is not a radius of MEMS gyro **200**, i.e., the vectors **340** do not all intersect at the origin of the x and y-axes. Nonetheless, the spring set of MEMS gyro **200** has quarter symmetry, meaning the four springs **224** taken together exhibit symmetry across both of two orthogonal axes, in this case the x-axis and the y-axis. Vectors **340** also exhibit quarter symmetry, and are off-axis with respect to the x and y-axes as are common radii **140** described above, and as such vectors **340** are not parallel to or orthogonal to the x or y-axis or any other two orthogonal axes with the same origin as the x and y-axes. In this configuration, MEMS gyro **300** is not axially symmetric about the z-axis, nor is there rotational symmetry about the z-axis (the z-axis is not shown in FIG. **13**, but see FIG. **2**).

Having the anchor points of spring elements **334** arranged on vectors **340** provides essentially the same advantages described above with respect to MEMS gyros **100** and **200**. While the spring set of MEMS gyro **300** has been shown in the exemplary context of a MEMS gyro with a single driven mass and spring set, those skilled in the art will readily appreciate that similar spring sets can be used in MEMS gyros with any number or driven or intermediate masses without departing from the spirit and scope of the invention.

The techniques and methods described herein effectively mitigate unwanted out of plane quadrature rotation along the y-axis in the driven mode and causes more out of plane rotation along the x-axis. This increase in x-axis rotation is not dynamically amplified, does not generate an electrical signal, and does not corrupt the desired output signal.

Those skilled in the art will readily appreciate that while discussed above in the exemplary context of DRIE tools, the invention can be practiced using any suitable tools without departing from the spirit and scope of the invention. Whether state of the art etching techniques such as in DRIE tools are used, or whether less precise techniques are used, the configurations described herein can yield reduced quadrature error over traditional spring set designs.

The methods and systems of the present invention, as described above and shown in the drawings, provide for spring set configurations for MEMS devices with superior properties including reduced quadrature error. While the apparatus and methods of the subject invention have been shown and described with reference to preferred embodiments, those skilled in the art will readily appreciate that changes and/or modifications may be made thereto without departing from the spirit and scope of the subject invention.

What is claimed is:

1. A spring set for a MEMS device comprising:

a) a plurality of springs connecting a first mass to a seconds mass, wherein the first and second masses define orthogonal x, y, and z-axes and are configured for relative oscillation about the z-axis, each spring having a spring element anchored to the first mass at a first anchor point and anchored to the second mass at a second anchor point, wherein the first and second anchor points of each spring element are located on a respective common vector that is oblique with respect to the orthogonal axes defined by the first and second masses, wherein the respective common vector is non-radial with respect to the z-axis.

2. A spring set as recited in claim **1**, further comprising one or more additional masses each attached to another one of the masses by a respective plurality of springs.

3. A spring set as recited in claim **1**, wherein the plurality of springs are arranged with quarter symmetry.

4. A spring set as recited in claim **1**, wherein each spring has a mass that is balanced about the respective common vector.

5. A spring set as recited in claim **1**, wherein each spring has a length that is balanced about the respective common vector.

6. A spring set for a MEMS device comprising:

a plurality of springs connecting a first mass to a second mass, wherein the first and second masses define orthogonal x, y, and z-axes and are configured for relative oscillation about the z-axis, each spring having a spring element predominantly oriented parallel to a common axis, wherein each spring element is anchored to the first mass at a first anchor point and anchored to the second mass at a second anchor point, wherein the first and second anchor points of each spring element are located on a respective common vector that is oblique with respect to both the common axis and an orthogonal axis defined by the first and second masses, wherein the respective common vector is non-radial with respect to the z-axis.

7. A spring set for a MEMS device comprising:

a plurality of springs connecting a first mass to a second mass, the first mass defining a plane, each spring including a spring element with a cross-section having an etch angle that is oblique with respect to an axis orthogonal to the plane, wherein the springs impart a characteristic component of motion out of the plane to the second mass that is substantially insensitive to variation in the process induced etch angle of the spring elements.

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